A precise new KLOE measurement of F_π with ISR events and determination of $\pi\pi$ contribution to a_μ for $[0.35, 0.95]$ GeV^2

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The KLOE experiment at the DAΦNE ϕ-factory has performed a new precise measurement of the pion form factor using Initial State Radiation events, with photons emitted at small polar angle. Results based on an integrated luminosity of 240 pb^{-1} and extraction of the $\pi\pi$ contribution to a_μ in the mass range $[0.35, 0.95]$ GeV^2 are presented, the systematic uncertainty is reduced with respect to the published KLOE result.

1. Introduction

The anomalous magnetic moment of the muon has recently been measured to an accuracy of 0.54 ppm [1]. The main source of uncertainty in the value predicted [2] in the Standard Model is given by the hadronic contribution, a_μ^{hlo}, to the lowest order. This quantity is estimated with a dispersion integral of the hadronic cross section measurements.

In particular, the pion form factor, F_π, defined via $\sigma_{\pi\pi} \equiv \sigma_{e^+e^-\to\pi^+\pi^-} \propto s^{-1}\beta_\pi^3(s)|F_\pi(s)|^2$, accounts for $\sim 70\%$ of the central value and for $\sim 60\%$ of the uncertainty in a_μ^{hlo}.

The KLOE experiment already published [3] a measurement of F_π with the method described below, using an integrated luminosity of 140 pb^{-1}, taken in 2001, henceforth referred to as KLOE05.

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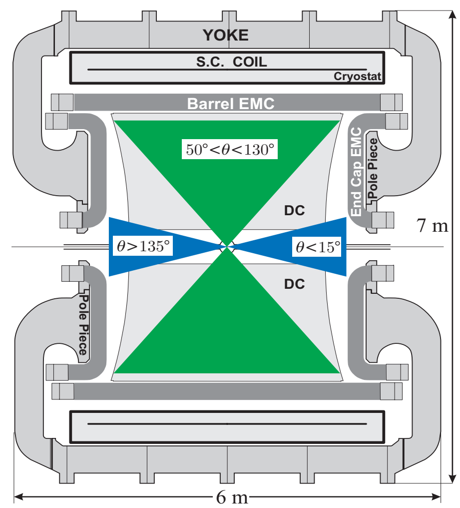

Figure 1. Fiducial volume for the small angle photon (narrow cones) and for the the pion tracks (wide cones).

2. Measurement of $\sigma(e^+e^- \to \pi^+\pi^-\gamma)$ at DAΦNE

DAΦNE is an e^+e^- collider running at $\sqrt{s} \simeq M_\phi$, the ϕ meson mass, which has provided an integrated luminosity of about 2.5 fb^{-1} to the KLOE experiment up to year 2006. In addition, about 250 pb^{-1} of data have been collected at $\sqrt{s} \simeq 1$ GeV, in 2006. Present results are based on 240 pb^{-1} of data taken in 2002.

The KLOE detector consists of a drift chamber [5] with excellent momentum resolution ($\sigma_p/p \sim 0.4\%$ for tracks with polar angle larger than $45°$) and an electromagnetic calorimeter [6] with good energy ($\sigma_E/E \sim 5.7\%/\sqrt{E\ [\mathrm{GeV}]}$) and precise time ($\sigma_t \sim 54\ \mathrm{ps}/\sqrt{E\ [\mathrm{GeV}]} \oplus 100\ \mathrm{ps}$) resolution.

At DAΦNE, we measure the differential spectrum of the $\pi^+\pi^-$ invariant mass, $M_{\pi\pi}$, from Initial State Radiation (ISR) events, $e^+e^- \to \pi^+\pi^-\gamma$, and extract the total cross section $\sigma_{\pi\pi} \equiv \sigma_{e^+e^-\to\pi^+\pi^-}$ using the following formula [7]:

$$M_{\pi\pi}^2 \frac{\mathrm{d}\sigma_{\pi\pi\gamma}}{\mathrm{d}M_{\pi\pi}^2} = \sigma_{\pi\pi}(M_{\pi\pi}^2)\ H(M_{\pi\pi}^2)\ , \tag{1}$$

where H is the radiator function. This formula neglects Final State Radiation (FSR) terms.

The cross section for ISR photons has a divergence in the forward angle (relative to the beam direction), such that it dominates over FSR photon production. The fiducial volume – shown in Fig. 1 – is based on the following criteria:

a) two tracks with opposite charge within the polar angle range $50° < \theta < 130°$;

b) small angle photon, $\theta_\gamma < 15°$ ($\theta_\gamma > 165°$), the photon is not explicitly detected and its direction is reconstructed from the track momenta in the e^+e^- center of mass system, $\vec{p}_\gamma = -(\vec{p}_{\pi^+} + \vec{p}_{\pi^-})$.

The above criteria result in events with good reconstructed tracks and enhance the probability of having an ISR photon. Furthermore,

- FSR at the Leading Order is reduced to the 0.3% level;
- the contamination from the resonant process $e^+e^- \to \phi \to \pi^+\pi^-\pi^0$ – where at least one of photons coming from the π^0 is lost – is reduced to the level of $\sim 5\%$.

Discrimination of $\pi^+\pi^-\gamma$ from $e^+e^- \to e^+e^-\gamma$ events is done via particle identification [4] based on the time of flight, on the shape and the energy of the clusters associated to the tracks. In particular, electrons deposit most of their energy in the first planes of the calorimeter while minimum ionizing muons and pions release uniformly the same energy in each plane. An event is selected if at least one of the two tracks has not being identified as an electron.

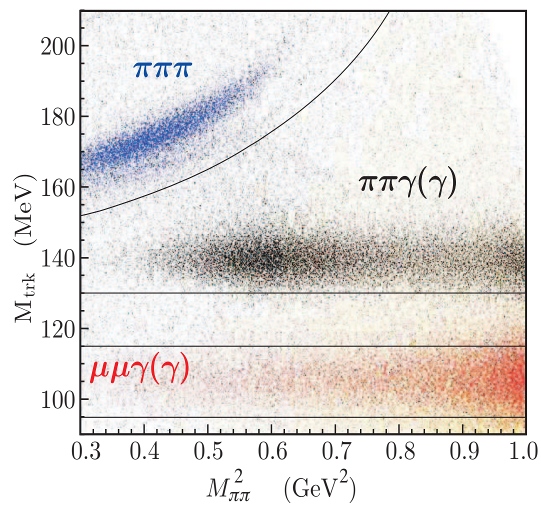

Figure 2. Signal and background distributions in the m_{trk}-$M_{\pi\pi}^2$ plane; the selected area is shown.

Fig. 2 shows that contaminations from the processes $e^+e^- \to \mu^+\mu^-\gamma$ and $\phi \to \pi^+\pi^-\pi^0$ are rejected by cuts on the track mass variable, m_{trk}, defined by the four-momentum conservation, assuming a final state consisting of two particles with the same mass and one photon

3. Improvements with respect to the published analysis

The analysis of data taken since 2002 benefits from cleaner and more stable running conditions of DAΦNE, resulting in less machine background and improved event filters than KLOE05. In particular, the following changes are implemented:

- a new trigger level was added at the end of 2001 to eliminate the 30% loss from pions penetrating to the outer calorimeter plane and thus were misidentified as cosmic rays events. For the 2002 data, this inefficiency has decreased down to 0.2%, as evaluated from a control sample;

- the offline background filter, which contributed the largest experimental systematic uncertainty to the published work [3], has been improved. The filter efficiency increased from 95% to 98.5%, with negligible systematic uncertainty;
- the vertex requirement on the two tracks – used in KLOE05 – is not applied, therefore eliminating the systematic uncertainty from this source.

The absolute normalization of the data sample is measured using large angle Bhabha scattering events, $55° < \theta < 125°$. The integrated luminosity, $\mathcal{L}$, is obtained [11] from the observed number of events, divided by the effective cross section evaluated from the Monte Carlo generator `Babayaga` [12], including QED radiative corrections with the parton shower algorithm, inserted in the code simulating the KLOE detector. An updated version of the generator, `Babayaga@NLO` [13], decreased the predicted cross section by 0.7%, while the theoretical relative uncertainty improved from 0.5% to 0.1%. The experimental relative uncertainty on $\mathcal{L}$ is 0.3%.

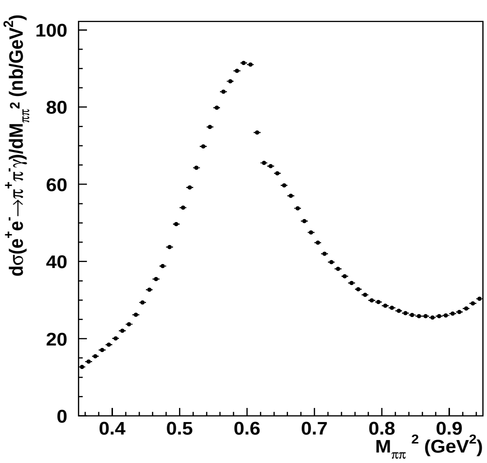

Figure 3. Differential cross section in the $\pi\pi$ invariant mass for the process $e^+e^- \to \pi^+\pi^-\gamma$, from an integrated luminosity of 240 pb^{-1}.

relative systematic errors on $a_\mu^{\pi\pi}$ (%)		
	KLOE05	KLOE08
offline filter	0.6	negligible
background	0.3	0.6
m_{trk} cuts	0.2	0.2
π/e ID	0.1	0.1
vertex	0.3	not used
tracking	0.3	0.3
trigger	0.3	0.1
acceptance	0.3	0.1
FSR	0.3	0.3
luminosity	0.6	0.3
H function eq.(1)	0.5	0.5
VP	0.2	0.1
total	1.3	1.0

Table 1
Comparison of systematic errors on the extraction of $a_\mu^{\pi\pi}$ in the mass range [0.35,0.95] GeV^2 between the analyses of different data sets.

4. Evaluation of F_π and $a_\mu^{\pi\pi}$

The $\pi\pi\gamma$ differential cross section is obtained from the observed spectrum, N_{obs}, after subtracting the residual background events, N_{bkg}, and correcting for the selection efficiency, $\varepsilon_{sel}(M^2_{\pi\pi})$, and the luminosity:

$$\frac{\mathrm{d}\sigma_{\pi\pi\gamma}}{\mathrm{d}M^2_{\pi\pi}} = \frac{N_{obs} - N_{bkg}}{\Delta M^2_{\pi\pi}} \frac{1}{\varepsilon_{sel}(M^2_{\pi\pi})\ \mathcal{L}} \ , \tag{2}$$

Fig. 3 shows the differential cross section from the selected events.

After unfolding, with the inversion of the resolution matrix obtained from Monte Carlo, for events with both an initial and a final photon,

$a_\mu^{\pi\pi}(M^2_{\pi\pi} \in [0.35, 0.95]\ \mathrm{GeV}^2) \times 10^{10}$ – KLOE	
published 05	$388.7 \pm 0.8_{stat} \pm 4.9_{sys}$
updated 05	$384.4 \pm 0.8_{stat} \pm 4.6_{sys}$
new data 08	$389.2 \pm 0.6_{stat} \pm 3.9_{sys}$
$a_\mu^{\pi\pi}(M_{\pi\pi} \in [630, 958]\ \mathrm{MeV}) \times 10^{10}$	
CMD-2 [17]	$361.5 \pm 1.7_{stat} \pm 2.9_{sys}$
SND [17]	$361.0 \pm 2.0_{stat} \pm 4.7_{sys}$
KLOE08	$358.0 \pm 0.6_{stat} \pm 3.4_{sys}$

Table 2
Comparison among $a_\mu^{\pi\pi}$ values evaluated with the small γ angle selection.

the differential cross section is corrected using `Phokhara` for shifting them from $M_{\pi\pi}$ to the virtual photon mass, M_{γ^*}. Then, it is divided by the radiator function (`Phokhara` setting the pion form factor $F_\pi = 1$) to obtain the measured total cross section $\sigma_{\pi\pi(\gamma)}(M_{\gamma^*})$, of eq.(1).

The pion form factor is evaluated subtracting the FSR term, η_{FSR} [15],

$$\sigma_{\pi\pi(\gamma)} \;=\; \frac{\pi}{3}\;\frac{\alpha^2_{em}\,\beta^3_\pi}{M^2_{\gamma^*}}\;|F_\pi|^2\,(1+\eta_{FSR})\;\;. \qquad (3)$$

The cross section for the $a_\mu^{\pi\pi}$ dispersion integral – inclusive of FSR – is obtained after removing vacuum polarization, VP, effects [14],

$$\sigma^{bare}_{\pi\pi(\gamma)} = \sigma_{\pi\pi(\gamma)} \left[\frac{\alpha_{em}(0)}{\alpha_{em}(M_{\gamma^*})}\right]^2 \;\;. \qquad (4)$$

Table 1 shows the list of relative systematic uncertainties in the evaluation of $a_\mu^{\pi\pi}$ in the mass range [0.35,0.95] GeV^2, for KLOE05 and for the analysis of this new data set, KLOE08.

5. Results

The published analysis, updated for the new Bhabha cross section and for a bias in the trigger correction [16], is compared with KLOE08, and also with the results obtained by the VEPP–2M experiments [17], in the mass range $M_{\pi\pi} \in [630, 958]$ MeV. Table 2 shows the good agreement amongst KLOE results, and also with the published CMD-2 and SND values. They agree with KLOE08 within one standard deviation.

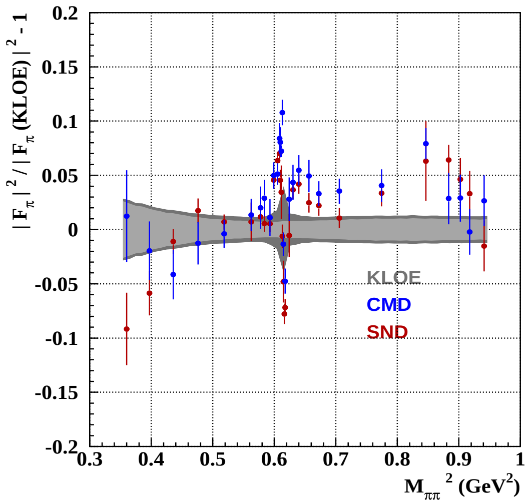

Figure 4. Comparison of the pion form factor measured from CMD-2, SND and KLOE, where for this latter statistical errors (light band) and summed statistical and systematic errors (dark band) are shown.

The band of Fig. 4 shows the KLOE08 pion form factor smoothed – accounting for both statistical and systematic errors – and normalized to fix the 0 in the ordinate scale. CMD-2 and SND data points are interpolated and compared to this band, in the same panel.

6. Conclusions and outlook

We obtained the $\pi\pi$ contribution to a_μ in the mass range $M^2_{\pi\pi} \in [0.35, 0.95]$ GeV^2 integrating the $\pi\pi\gamma$ differential cross section for the ISR events $e^+e^- \to \pi^+\pi^-\gamma$, with photon emission at small angle:

1. KLOE08 confirms KLOE05, but with more accuracy;

2. KLOE08 is in agreement within one standard deviation with SND and CMD-2 values in the mass range $M_{\pi\pi} \in [630, 958]$ MeV [17].

Thus, $a_\mu^{\pi\pi}$ is measured to an accuracy of 0.1%. Independent analyses are in progress:

- measure $\sigma_{\pi\pi(\gamma)}$ using detected photons emitted at large angle, which would improve the knowledge of the FSR interference effects from KLOE $f_0(980)$ measurements [18,19];

- measure the pion form factor directly from the ratio, bin-by-bin, of $\pi^+\pi^-\gamma$ to $\mu^+\mu^-\gamma$ spectra [20] (see Fig. 2 for the selection of $\mu\mu\gamma$ events);

- extract the pion form factor from data taken at $\sqrt{s} = 1$ GeV, off the ϕ resonance, where $\pi^+\pi^-\pi^0$ background is negligible.

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